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COMMISSIONING

(PHASE 4B)

FINAL TECHNICAL REPORT

by

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United States Army

EUROPEAN RESEARCH OFFICE OF THE U.S. ARMY

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SUMMARY

Following the BAA of December 1988, ANS&A proposed the creation of a new physical modeling research center at the Waterways Experiment Station. This new center would have, as its main research tool, a large beam centrifuge. The center would be attached to the Geotechnical Laboratory at WES, but would provide research facilities across the breadth of engineering research undertaken by the Corps of Engineers. The new Center was inaugurated on 21 November 1997, and this final technical report records the history and arguments in favour of centrifuge modeling as a powerful research technique in civil engineering. In the months since its commissioning the Centrifuge Research Center at WES has proved a world class facility and is already generating important data in a range of fields including geotechnical engineering, earthquake and environmental engineering, cold regions engineering, mobility, blast effects and groundwater studies.

LIST OF KEYWORDS

centrifuge
test
model
capabilities
research
containment
buildings
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appurtenances
instrumentation
safety
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1.0 COMMISSIONING OF THE ARMY CENTRIFUGE

1.1 RESEARCH BACKGROUND

This report is one of a series of reports prepared by Andrew N Schofield & Associates Ltd (ANS&A) addressing the development and commissioning of new capabilities for physical modeling research at the Waterways Experiment Station (WES), through the acquisition of the powerful Army centrifuge facility. The research described herein forms Phase 4B of the programme of work first proposed under ANS&A's response (of 17 April 1989) to the WES Broad Agency Announcement (BAA) of December 1988.

Phase 1 of this project, entitled "Safety Factor Analysis for Centrifuge Systems", addressed the specification, Quality Assurance (QA) procedures and safety of operations that would be required to successfully commission a new centrifuge center at WES. In the Final Technical Report under Phase 1 (Contract Number DAJA45-90-C-018), ANS&A (1992), it was recommended that WES should buy the Acutronic 684-1 centrifuge subject to the implementation of QA procedures designed to ensure the swift integration of the new facility into the research activities of WES, Schofield and Steedman (1991).

Phase 2 of this project (Contract number DAJA45-91-C-0012) entitled "Development of a WES Centrifuge" initiated the Quality Assurance process under which ANS&A worked with the Laboratories of the US Army Corps of Engineers through the Centrifuge Coordinating Committee to prepare specifications for appurtenances and data aquisition equipment that would be needed during the commissioning of capabilities. ANS&A's Phase 2 Final Technical Report made specific recommendations concerning the development of appurtenances for initial experiments which would be compatible with the design of the Acutronic 684-1 centrifuge, Schofield and Steedman (1992).

Phase 3A entitled "Centrifuge facility design and development of capabilities" (Contract number DAJA45-91-C-0025) and 3B "Report on Quality Assurance for the WES Centrifuge" (Contract number DAJA45-92-C-0021) addressed the continuing role of ANS&A in providing advice and guidance during the design phase of the WES Centrifuge by Acutronic France SA. ANS&A's Final Technical Report covering Phases 3A and 3B recommended acceptance of the detailed design of the Acutronic 684-1 centrifuge and that the operating envelope of the centrifuge be revised to maximise the potential capability of the facility in the mid-range of operating levels (150-350g), Schofield and Steedman (1993).

Phase 3C, entitled "Coordination of operations for centrifuge quality control" (Contract number DAJA45-93-C-0021), presented recommendations concerning the initial research experimentation on the WES centrifuge and addressed in detail the mechanical commissioning of the centrifuge following its arrival in Vicksburg. A key recommendation arising from Phase 3C was the separation of the initial mechanical commissioning (upto a level of around 250 gravities) from the final commissioning (to full capability) and the necessity for careful and close control of the commissioning operations, Schofield and Steedman (1995). This approach was considered essential because of the unique nature of the centrifuge and the uncertainty over the available Manufacturer's documentation concerning Quality Control.

Phase 3D, entitled "Integration" (Contract number N68171-94-C-9066), addressed the preliminary experiments being planned to demonstrate the range of novel capabilities achieved for the new facility. Recommendations were also made on staffing for the facility and a set of operating procedures were prepared for general use, Schofield and Steedman (1995).

Phase 3D was followed by Phases 4 (Contract Number N68171-95-C-9047) and 4A (Contract Number N68171-97-C-9013). In reviewing the history of the project leading upto the inauguration of the new research center it was concluded that three main factors could be identified which had contributed to the success of the project. These were a) the focus on the research product, which led to early investment in general purpose and specific test equipment and appurtenances so that a rapid start could be made on use of the facility, b) an emphasis on safety of components and safety of operations, and c) the continuity of staff working on the project, at WES, within ANS&A and with the centrifuge designers in France.

This Final Technical Report covers the subsequent contract Phase 4B (Contract Number N68171-97-M-5713) entitled "Commissioning", which followed the process of commissioning of the WES centrifuge center in the months immediately before and after the inauguration of the centrifuge facility on 20 November 1997.

1.2 THE BAA

The BAA of December 1988 stated that;

"... physical modeling methodology ... can be used for (1) complicated problems for which calculation methods are not completely reliable or adequate and prototype behaviors can not be reliably predicted, (2) validation, improvement and development of numerical methods for prototype behavior, (3) parameter studies to find out more about particular properties and behaviors in relation to variations in loads and other boundary conditions, and (4) studying the important behavior phenomena including failure that are impracticable or not feasible to induce in prototype situations or for complex problems. Areas of interest include shock, earthquake, and explosives testing ... soil and components ... water ... frozen water ... and ice ... hydraulic structures ... coastal structures ... and waves ... pollutant in soil and groundwater ... geologic process and ... structures ... modeling of prototype processes such as construction, excavation, filling and drawdown of reservoirs, ... Internal measurements ... and probing models"

ANS&A's response to the BAA identified the long experience of the USAE in physical modeling of civil engineering problems and stressed the wide range and importance of the work of the Corps in engineering design and public safety.

Under the BAA, ANS&A has provided advice and technical support in the development of an extraordinary and world class center for engineering research using physical (centrifuge) modeling. The small scale models of field problems which can be undertaken in the new facility have already started to make an impact on design approaches, particularly in the field of earthquake engineering. More work will follow.

2.0 GEOTECHNICAL CONTEXT

2.1 SMALL SCALE MODELING AND FULL SCALE FIELD OBSERVATIONS

The BAA of December 1988 reflected a transition of physical centrifuge modeling into being an engineering tool from the academic research environment in the world of field problems and engineering solutions. Centrifuge modeling is now well established as a technique by which deep insights may be gained into the behaviour of soil and soil-structure systems. The value of the centrifuge model to the engineer is precisely that physical models exploit the true nature of the soil behavior itself. Field observations of many soil phenomena may be replicated in the laboratory by scale models using remoulded soil. The strength of such soil is governed by the mechanical properties of the aggregate of particles and not by chemical bonding or other explanation.

The route by which this concept became a reality was tortuous. Many challenges still face innovators in modeling today. As the new Centrifuge Research Center at the Waterways Experiment Station becomes further established within the engineering community, the geotechnical context must not be forgotten.

As early as 1936, at the first International Conference of International Society of Soil Mechanics and Foundation Engineering (ISSMFE) at Harvard from June 22 to 26, Karl Terzaghi expressed his views on the subject of geotechnical theory :

"some eighteen years ago ..(i.e. in 1918, when).. I went through all the volumes of the leading English, German, and French engineering periodicals which had been published since 1850 and through all the textbooks which I could secure, abstracting all the articles and chapters relating to the subject of my investigations... (When) the theories originated, their authors were still keenly aware of the bold approximations involved, and nobody thought of accepting them at their face value. As the years passed by, these theories were incorporated into the stock of knowledge to be imparted to students during the years of their college training, whereupon they assumed the character of a gospel. Once a theory appears on the question sheet of a college examination, it turns into something to be feared and believed, and many of the engineers who were benefited by a college education applied the theories without even suspecting the narrow limits of their validity. If the structures designed on the basis of these sacred theories stood up, their behaviour was considered normal and not worth mentioning. If they failed it was an act of God, which should be concealed from the eyes of mortals, who might believe the designer was poorly grounded in theory."

Many engineers today would agree that such a comment was as apt now as it appeared to Terzaghi then. The Harvard Proceedings must be read in full to give a sense of the mixture of enthusiasm and scepticism with which Terzaghi launched the new International Society.

Terzaghi (1936) placed importance on observations by engineers during construction, such as in the building of the Panama Canal, or in the construction camps of the US Bureau of Reclamation. He said, "(In) the perpetual war of the civil engineer against the treacherous forces of nature concealed in the earth ... scattered and world-wide efforts extending over a period of 25 years (have forged) new and efficient weapons and the prime purpose of our meeting consists in discussing the means of exploiting the advantages thus secured, ... (The) possibilities for successful mathematical treatment of problems involving soils are very limited. (The) accuracy of computed results never exceeds that of a crude estimate, and the principal function of theory consists in teaching us what and how to observe in the field. (Successful) work in soil mechanics and foundation engineering requires not only a thorough grounding in theory combined with an open eye for the possible sources of error, but also an amount of observation and measurement in the field far in excess of anything attempted by the preceding generations of engineers. Hence the centre of gravity of research has shifted from the study and the laboratory into the construction camp where it will remain".

The International Society also published a paper on the use of small scale centrifuge models by G I Pokrovsky (1936). However, Terzaghi strongly criticised all papers on small scale physical modelling as "papers whose authors do not hesitate to generalise the conclusions derived from pure theory or from small scale tests on materials with very little if any resemblance to real soils". He stated that "One of the principal goals of instruction in soil mechanics should be to discourage this prevailing tendency to unwarranted generalisation." He went on to speak of "the utter futility of the attempts to discover any single-valued relation between the results of small-scale loading tests and of the settlement of large foundations on stratified soils".

This comment on the lack of value of small scale modeling proved to have unfortunate consequences. The problems that engineers face are so complex that they should never dismiss any technique until it is proven to be unsound. Although it is now clear that centrifuge tests can solve problems where observation at full scale is no help, for many decades the engineering community neglected this valuable technique, having been directed away from it at an early stage.

Today there are many examples where centrifuge modeling has provided direct and substantial benefits to the engineering community. One such example is in the field of offshore engineering, where "measurement in the field" is extensively used, and the overturning failure of a jackup rig in storm loading has been successfully studied in a centrifuge at small scale, in reduced time, at low cost, and not at full scale. Other conditions which can and should be studied in small scale tests include, tidal flood, river flood, earthquake damage, and prolonged contaminant migration. There are many advantages to the use of model tests over field experiment, not least that a model test of a violent event has no publicly unacceptable environmental impact or risk.

2.2 THE SUCCESS OF SOVIET CENTRIFUGE MODELING

The most serious consequence of this error of judgement came during the Cold War, after the full scale Nuclear Test Ban, when the US and NATO Allies missed an opportunity to study nuclear weapons effects in centrifuge models. Pokrovsky's centrifuge paper opens with a statement that in 1936 the laboratory for Physics of the Military-Engineering Academy of the USSR used a centrifuge. But it was not until the 1973 ISSMFE Moscow Conference when the Soviets invited participants who were interested in centrifuge techniques to a meeting for open discussion with Pokrovsky and other Soviet engineers, at the Hydroproject after the Conference, that it became clear how extensive had been their development of this technique. At that time Western experts thought there had been difficulties by which Pokrovsky's techniques proved to be less useful than he had hoped in 1936. But it quickly became clear that the Soviets wanted the West to become more fully aware of Pokrovsky's work. A book by

Pokrovsky showed that the Soviets had successfully modelled nuclear weapons craters using centrifuges. The Hydroproject itself had a powerful centrifuge facility.

The work in the USSR was brought to the attention of the US scientific community. The US Defence Nuclear Agency later sponsored crater tests in the Boeing Company centrifuge in Seattle, which led to an order of magnitude reduction of crater size prediction at nuclear explosive levels. In his paper for the ISSMFE San Francisco conference, Schmidt (1988) wrote;

"Results of recent geotechnical centrifuge experiments have dramatically reduced the size estimates for craters formed by near-surface large yield nuclear explosions and by planetary impact of large bodies. Since neither phenomenon can be tested at full scale, centrifuge simulation is the only alternative for obtaining an experimental data base. Estimates of crater size were reduced due to the identification of a strength-gravity transition size, above which cratering efficiency decreases with size. Existing field data were too sparse and were conducted in far too diverse media to observe this pattern. The geotechnical centrifuge has been a valuable experimental technique for investigating explosive and impact cratering behaviour. (The tests) establish the practicality of performing dynamic experiments on the centrifuge, as well as providing a theoretical basis for their interpretation."

Terzaghi's 1936 words on the "utter futility" of small scale tests effectively postponed the development and use of small scale physical model tests in the West for many years, leading to a heavy reliance on the new, computational methods when they started to emerge during the 1960s and 1970s. Without the benefit of validation by an alternative technique it was much less likely that the West would find or correct errors after full scale tests were banned; Schmidt's comment above shows clearly the consequences of relying on theoretical engineering calculations without an effective validation technique. In contrast, Pokrovsky's "efforts" gave the Soviets a "new and efficient" research asset. After his early centrifuge model experience he worked on weapons effects during and after World War II. As an expert on cratering he was part of a Soviet elite (he had the rank of Red Army General and Stalin came to parties where Pokrovsky played the piano at home).

The military potential should have been evident at Harvard, where it is clear in Pokrovsky (1936) that small scale tests did work. The detailed experimental technique and promising results are as evident in that paper, as they are in Volume I of Centrifuge 98, the forthcoming International Conference on Centrifuge Modeling to be held in Tokyo, which has 147 such papers to consider. At the ISSMFE Tokyo Conference in 1977, when Soviet participants said that the centrifuge was mainly of military significance, Western experts commented that centrifuge techniques had a fundamental scientific significance and were well based in experimental mechanics. Critical state soil mechanics showed reconstituted soil paste to be an effectively stressed elasto-plastic inviscid material in which time effects are due to consolidation. The Soviet analysis in terms of total stress and viscosity made collaboration with Soviet engineers difficult. Western centrifuges were designed with a capability of pore pressure measurement, which was not available to the Soviet engineers because of their lack of solid state instrumentation and pc based data aquisition systems. In spite of the large investment that the West has made in geotechnical centrifuges, it is not until very recently that Western centrifuges have approached the carrying capacity of the typical Soviet centrifuge twenty-five years ago.

2.3 CIVILIAN CENTRIFUGE CAPABILITIES IN THE WEST

Outside the Soviet Union, centrifuge modeling as a scientific technique had a difficult birth. Its adoption and development as a research tool (particularly in Europe and Japan) amongst academic institutions in the 1960s and 1970s owed much to the 'new' thinking known as Critical State Soil Mechanics within which soil behavior could be analysed and predicted in terms of effective stresses and mechanical strains. Other phenomena, of more direct interest to Western civil engineers than weapons effects, were quickly reproduced in centrifuge model tests. Experiments of the failure of trench headings, tunnels and slope stability showed a level of detail which had hitherto been impossible to discern from field observations. From these and many other field problems involving 'static' loading conditions there developed interest in modeling civil engineering problems involving dynamic loads, such as earthquake and soil liquefaction. These were generally 50-100g centrifuge model tests; they showed clearly all the phenomena that had been observed hitherto only in the field.

Within the international community there is now an acceptance of Terzaghi's effective stress principle, and the technical committee on centrifuge modeling of the ISSMFE, TC2, has allowed an easy international exchange of information between more than 30 centrifuge centres. A series of international centrifuge conferences, starting in Paris in 1988, and leading up to the forthcoming Tokyo conference, have shown the extraordinary blossoming of international interest in this technique as a means of analysing soil behavior in field situations. By combining laboratory element tests, used to discern fundamental soil properties, and centrifuge model tests where the soil is treated as a reconstituted aggregate (soil 'paste'), a wide range of field design problems may be addressed. Both laboratory test and centrifuge model are considered as small scale loading tests and complement each other in the engineering solution. A shear test at very small scale (say on 0.1 to 1 litres of soil) defines soil properties, and a centrifuge model at larger scale (say on 100 to 1000 litres of soil) give data of behaviour of soil under field gradients of effective stress and pore water pressure. These two sets of test data are sufficient to provide a thorough test of theories, in the "study and the laboratory". This method was used in a US National Science Foundation project on verification of liquefaction analyses, Arulanandin and Scott (1994).

The international co-operation which is now apparent mainly concerns construction works and models made of fill or disturbed soil or ground conditions which may be treated as such (e.g. soft clay). There are now numerous examples of the application of centrifuge modeling directly addressing field design problems. Centrifuge model tests have been incorporated into the design process as another tool, particularly valuable in the validation of analytical and numerical solutions and the prediction of the onset of damage. For much construction, it is clear that soil tests could be readily used to find the critical state properties of soil selected for a fill, or of soil at a selected site. Construction budgets could include the cost of tests to failure of centrifuge models, and observational methods could be based on such tests. Engineers such as those involved in foundations of offshore structures in Exxon Production Research, now turn to centrifuge studies, particularly if ground is disturbed or improved, for validation of numerical analyses.

However, although this extensive Western capability development has taken place, it is striking that there are still no facilities operating at over 200g except in WES and at Cambridge.

3.0 BEAM AND DRUM CENTRIFUGE DESIGN

3.1 POKROVSKY'S BEAM CENTRIFUGE

The centrifuge at the WES is described as a beam centrifuge, in which a large balanced beam rotates in a horizontal plane about a central vertical axis. This is similar in concept to the early Soviet centrifuges. Pokrovsky (1936) Fig. 1 shows a 30g centrifuge made from parts of a Ford truck. One half-shaft stands vertically upright above the differential. The centrifuge rotor replaces a back wheel. The rotor arms slope at 1/30. They act as tension members. (In that sense Pokrovsky's centrifuge is not a "beam" centrifuge.) The model containers swing up about hinges. They are shown end on. In his test a load bears on a plate, and pressures are measured below the ground surface. In his Fig. 2 vertical pressure is plotted against depth with five lines showing pressure as follows;

in ground with self weight, and

I in an elastic half space under vertical load, and
II the sum of these two previous pressures, and
III pressures measured in Pokrovsky's centrifuge model test, which agree with
IV pressures observed in a full scale test.

Pokrovsky draws a pressure gauge in his Fig. 3. A short length of broken capillary tube was pressed into a small tin full of pink petroleum jelly. The air filled space inside the tube was closed by pink jelly at each end. A rubber membrane covered the jelly. The tin was buried in the model. The model was subjected to high acceleration. The burette was opened. Fluid flowed down along the axis and out to a vessel which applied the required bearing load. After a test the tin was removed and the capillary tube was examined. The pressure increment had compressed the air. Jelly had moved into the ends of the tube leaving a pink stain. Pokrovsky determined the maximum pressure, at that depth, from the minimum length of the air bubble. Both in the full scale test and in the model test he measured pressures up to 50 percent higher than he had calculated theoretically. He had proved that his technique worked, and it was applied to a series of problems where there were no reliable theoretical calculations.

Malushitsky (1975) described the application of Pokrovsky's technique to problems of mine waste embankments. It gave him a capability for analogue modelling of a problem which he could not solve numerically, with the facilities available to him. His centrifuge could achieve 320g but typical tests were at below 200g. The inside dimensions of his model were length 1400mm, width 500mm, height 750mm, corresponding at 320g to a prototype volume of 17.2 million cubic metres. He built up models in successive layers of reconstituted waste material which he consolidated in flight for long periods. He tested his models by rapid increase of acceleration until there was a slope failure. Academics in the USSR at that time analysed soil as a viscous material under total stress. The scale of time was expected to be the model scale to some power between 0 and 2. Malushitsky found a value of this factor that was appropriate to his class of problem by the technique of modelling the model. His simple instrumentation and the variability between successive models meant that his work took many years. He tested 255 models in total, and writes that they resulted in elimination of landslides at the waste heaps of an open-cast sulphur mine, reduction in re-excavation in internal dumps in an open cast coal mine, and safe tipping of new dry waste on old hydraulic lagoon disposal areas, with savings to industry of about three quarters of a million roubles per year.

Beam centrifuges require careful consideration of safety containment, and this generally involves a strong, purpose built chamber to protect workers from a catastrophic accident. The WES centrifuge center is designed to provide level separation between the plane of the rotating centrifuge and the operators and office accommodation. Access to the centrifuge for ease of loading and unloading potentially bulky and heavy packages is also essential, and at WES a large armoured door in the chamber wall provides direct access on the same level to the model preparation area, which is immediately adjacent to the centrifuge chamber. The model preparation room is fully equipped with laboratory services and heavy lifting equipment and direct vehicular access to the outside. This design provides a comfortable and attractive working environment.

Most Western centrifuges are beam centrifuges, many of which are 200g centrifuges made by Acutronic France. When the Army asked Acutronic to design the Army centrifuge, the increase of acceleration from 200g to 350g carried Acutronic into a new design area. It also raised the question of whether or not it would be possible to develop instrumentation and to acquire data from model tests at these high accelerations, where previously there was little data above 125g and none above 200g. All Soviet tests were uninstrumented and crude, but effective. In Cambridge the 2m drum had run at 500g with one (uninstrumented) cubic metre of water. The objective of ANS&A in drum development was to develop instruments and acquire data at 350g, ahead of the WES development. In future it is anticipated that new drum centrifuges will be used in centrifuge centers to complement the traditional beam centrifuge and to extend the range of field problems that may be addressed.

3.2 DRUM CENTRIFUGE DESIGN

In Cambridge, England a drum centrifuge design has been developed which is intended to reduce the cost of centrifuge tests, to improve the accuracy, and reduce the labour and the time needed for any one test series. The Cambridge design is now being manufactured commercially. One of the new units is in operation in Australia, Stewart, Boyle, and Randolph (1998); three others are operating in Japan; and a fifth is to operate in Switzerland. A key advantage of such machines is the reduced need for safety containment; there is no need to build a reinforced concrete chamber. The centrifuge channel that applies the acceleration to the model layer also contains the soil safely.

In a 2.2m diameter drum centrifuge a channel 0.8m high with 0.2m depth filled with soil forms a single model of large volume and surface. In flight at 320g it is a model of a test site about 2000m long, 256m wide and 64m deep, with a prototype volume of 32.8 million cubic metres. This may be contrasted with the maximum dimensions of a test site that can be modeled on the WES beam centrifuge at 350g, which would be 420m in diameter and 350m deep, giving a prototype volume of around 48.5 million cubic metres. The drum centrifuge provides an excellent capacity for multiple experiments involving shallow (near surface) phenomena, although it cannot compete with the depth of specimen which can be investigated on a large radius and capacity beam centrifuge such as the one at WES. The large surface area of the test site makes the drum particularly useful for rapidly completing a large series of similar experiments, such as footing tests.

A special feature of the Cambridge drum centrifuge design is its capacity for continuous safe operation. Model preparation in the channel, and setting up the test procedure, takes time, but if the test process is automated the channel can then be in continuous flight for several weeks. To change tools which are manipulated and work over the model in flight, a safety shield is lowered to isolate the central plate that supports tools. After this work support is brought to rest, tools can be changed; when it is bought back to channel speed and the shield is raised new tools can work over a chosen test site. Stewart, Boyle, and Randolph (1998) describe both an automated testing system and a data acquisition system. Similar rugged and compact systems were provided for the WES beam centrifuge, and to Toyo Construction Technical Research Institute, Hyogo, Japan, by Carrak (1998), acquire digital data at 5000 samples per second in memory in a logger unit close to the model in the high g field, for uploading to a PC at the control desk. Drum and beam centrifuges operate side by side in centrifuge centres in the UK, Japan, and Australia and complement each other. Any manipulator used in a drum centrifuge can be controlled from the centre of the drum at low g. When both beam and drum centrifuges are used on a single project, test equipment can be transferred from one machine to the other.

One recent example of the successful application of complementary testing on the beam and the drum centrifuge is in the field of offshore engineering. In a jackup platform, the three legs apply cyclic loads of the order of ten thousand tonnes to spud cans bearing on a sea bed. Jackup spud fixity was modelled in the Cambridge 10m diameter beam and 2m diameter drum centrifuges, and Dean et al (1993) studied the bearing capacity of conical footings on sand in relation to the behaviour of spudcan footings of jackups, as part of theoretical and experimental studies undertaken over a period of several years. The work as reported in publications and Cambridge University theses (e.g. Tsukamoto PhD (1990) tested foundation fixity of a model jackup with three independent legs, deployed at successive locations on a model "sea bed" round the wall of the 2m drum). This work has led directly to a revised design approach. Foundation fixity now is described by a yield locus rather than by "bearing capacity factors". The model test data are equivalent to observations of limit states in hundreds of storms offshore. The offshore industry has good experience of both beam and drum centrifuge modelling. Each year the offshore industry deploys jackups for ever longer periods in ever deeper water, and needs ever better guidance to select units that are appropriate for successive projects.

It was a special feature of the work of ANS&A in assisting the Army in the development of their centrifuge that parallel work on the novel drum centrifuges in Cambridge had already proved the value of some instrumentation. For example, the Druck pore pressure transducers which were recommended to the Army had already been used at 300g in the drum centrifuge.

4.0 EARTH PRESSURE THEORIES AND CENTRIFUGE MODELS MADE OF RECONSTITUTED SOIL

4.1 THE SIGNIFICANCE OF STRAIN

Reconstituted or remoulded soil fill is widely used for construction and in many cases design is concerned with plastic yielding of such soil. Observational methods are often used as a part of the design process for construction in intact (undisturbed) soil. Centrifuge models are made of reconstituted soil and as such have a close relationship to theory of plastic design. They have less bearing on the study of the non-linear elastic behavior of intact soil.

In 1929 Terzaghi made full scale tests on retaining walls constructed with soil fill, and he makes his mistrust of earth pressure theory clear in the title of a paper that he presented to the Boston Society of Civil Engineers on May 20, 1936, "A fundamental fallacy in earth pressure computations", (the only paper reprinted in full in the 1936 Proceedings). He draws attention to small ground movements that he observed and asks how forces measured in trench supports relate to strain in the ground beside the trench. He complains that "the factor 'strain' does not enter the theory" and his first conclusion is that

"The fundamental assumptions of Rankine's earth pressure theory are incompatible with the known relation between stress and strain in soils, including sand. Therefore the use of this theory should be discontinued".

This was an insightful remark, but in spite of this, Rankine's theory is still in general use today, over 60 years later, see for example, Terzaghi, Peck and Mesri (1996). This may have been for pragmatic reasons at the time and a lack of understanding of the nature of soil dilation, but it has since been addressed, at least in stress states governed by rupture and slippage.

Limiting plane equilibrium satisfies the two equations,

$$\delta\sigma_x/\delta x + \delta\tau_{xy}/\delta y = 0\,,$$

$$\delta\tau_{xy}/\delta x + \delta\sigma_y/\delta y = 0\,.$$

Coulomb solved by statics some problems of plane bodies for which the limiting stress criterion has a form

$$F(\sigma_x,\tau_{xy},\sigma_y)=0\,.$$

This system of three equations in the three unknowns $(\sigma_x,\tau_{xy},\sigma_y)$ is of the hyperbolic type. Strain has no place in the mathematics. For a criterion $F = 0$ of the Mohr Coulomb type, where

$$F = \{[(\sigma_x+\sigma_y)/2 + c\cot\phi]\sin\phi\}^2 - [(\sigma_x-\sigma_y)/2]^2 - \tau_{xy}{}^2 = 0$$

and the limiting 'envelope' is defined by the well known expression

$$\tau = c + \sigma \tan \phi$$

in a plane limiting stress field, there are two characteristic directions along each of which a function of the magnitude and direction of stress maintains a constant value. Stresses are defined at each point on a particular length of boundary, and in a triangular "domain of dependence" the stress at a place in the domain is fixed by values of these functions that are propagated to that place along the two characteristics that reach that place from two points on boundary. The only good reason for use of the equations to be discontinued is that one or other of the equations does not apply. The equilibrium equations are beyond question. But, from the fact that strain does affect earth pressures, it is clear that the Mohr Coulomb equation is inadequate to describe accurately soil behavior in the field; cohesion and friction cannot both be "true" soil constants; they must introduce the strain boundary conditions into the solution of the system of equations, Schofield (1998).

One of the most common areas in practice where blanket acceptance of the Mohr Coulomb equation causes difficulties is in the prediction of slope stability. Laboratory element test data are frequently conducted at higher confining stresses than are present in the field and do not provide comparable strain boundary conditions from which useful guidance may be reached on the margin of safety of the slope in the field. Scale model tests in a centrifuge, combined with carefully selected laboratory element tests, would provide the engineer with the appropriate information for design. One of the early demonstration experiments on the WES centrifuge was to study the slope stability of steep slopes cut into the Vicksburg loess, and to demonstrate failure mechanisms identical to those observed in the field. These cannot be reproduced by use of the Mohr Coulomb equation alone.

There is therefore a close link between the development of centrifuge model tests and a "true" understanding of the nature of soil as a plastic material. Engineers who are unaware of the significance of strain in soil behavior will not appreciate the added value of centrifuge model tests.

4.2 SOIL BEHAVIOR

In over consolidated clay (or in dense sands) the peak strength increases because the particles become densely packed, not because of molecular attraction of "cohesive" soil particles. Critical state friction is the reliable part of clay peak strength. There is an unreliable transient part of the peak strength of soils due to "interlocking", Taylor (1948), which is the same as "arching". We can see from the increased water content in gouge material on slip surfaces, that stiff clay at peak strength is dilating as it shears and softens. Peak strength instability is like buckling in the sense that it involves geometry and strain boundary conditions. It is not defined uniquely in stress space, as illustrated by the problem of considering Mohr's circles as if they represented a single "true" curved failure envelope which can be fitted approximately by the Mohr Coulomb equation.

Neither Coulomb nor Rankine tested soil in a shear box. They distinguished between solid rock which exhibited strength in a tensile test, and soil whose disturbed parts do not adhere. They saw that a drained slope of soil has an angle of repose which they called the angle of friction. This was the strength parameter that they relied on in design. For the angle of repose to be a soil constant, all shear deformation down slope must be at constant volume. Soil which deforms continuously at constant volume, in a drained shear test or below a slope at repose, must be in critical states with $q=Mp'$. This applies equally to soil with coarse and with fine grains.

Schofield and Wroth (1968) describe liquid limit tests as undrained behaviour of soil in critical states. The apparent cohesion of test samples of fine grained soil with low permeability is equal to suction times critical state friction. It increases as effective stress increases. Soil yields in a stable manner on the wet side of critical states, at stress ratios less than critical, where $q<Mp'$. Plastic yielding of such soil is predicted by the cam clay theory.

Failure with $q>Mp'$ on the dry side of critical states involves unstable behaviour. Faulted soil dilates in shear, causing water to be sucked into slick soil paste on the failure plane.

A centrifuge model made of reconstituted soil paste can have zones of plastic yielding, or zones of unstable faulting, as if very many elementary volumes of soil stacked together each experienced a different true triaxial test, with compression and shear strain on the wet side of critical states and rupture on the dry side. A particular soil can exhibit anisotropy if it has such tendencies. The geotechnical centrifuge is a good apparatus for testing reconstituted soil on the wet side of, or near to, critical states.

At very low effective stress, soil will fissure. If there are cracks, pipes, or channels in a zone across which there is a high hydraulic gradient, rapid transmission of pore pressure into the soil it will transform what was initially a stiff, lightly stressed, continuous soil body into a clastic debris flow. When this effect is seen in centrifuge model tests it is described as liquefaction. Some effects may not scale, and care is needed. Whenever it is claimed that progressive failure at homologous points in a model and a prototype are similar, the interlocking geometry, effective stress, and transient seepage flow all have to be correct within the zones through which instability propagates. This can be validated by modelling of models.

Thus soil on the dry side of critical state and on the wet side can be reliably modeled using remoulded soil models in a geotechnical centrifuge. Reconstituted soil can be used to make centrifuge models of any material that is selected for a compacted fill. The same technique is used for sites chosen for construction requiring compaction or other improvement of the ground. But there are limitations. Materials with which engineers must work in the ground range from rock to soft rock to soils in which chemical and other processes have partially or wholly transformed the original deposits, and more work is needed on ageing, creep, and cohesive bonds before reliable models can be made of ‘so-called’ undisturbed ground or soft rock.

5.0 CONCLUSIONS

The new Centrifuge Research Center at the WES is already producing experimental data which will have a direct impact on the engineering design process. The facility is world class, and provides the Army with an extraordinary new capability for physical modeling.

The new Army capability exceeds the capabilities of the Soviet centrifuges developed twenty-five years ago not simply in carrying capacity, but in the complex instrumentation, robotic tools and data acquisition systems which provide information on the behavior of the specimens to an unprecedented degree. Experience of the use of instrumentation at very high gravities in drum centrifuges in Cambridge played a signficant role in the development of the new research facility.

There is a close link between the understanding of soil behavior and the logic of centrifuge model testing. Centrifuge model test specimens are free to show significant plastic strain in mechanisms of deformation. Tests in which models suffer large strains disclose the three regimes of large strain behaviour, (fissure, fault, fold), that may be seen at full scale. Centrifuge tests complement observational methods, with larger strains and more extensive parametric studies than are achieved in the field. The test data may be used to validate numerical models; each small scale test has a fundamental basis in applied mechanics. Small scale model tests on a centrifuge, combined with carefully selected laboratory element tests, will provide the engineer with appropriate information for design. Limit states can be achieved and studied in centrifuge tests where soil specimens are permitted to strain upto and even beyond a 'failure' criterion.

Much of the added value of centrifuge modeling (for geotechnical problems in particular) lies in this ability of the specimens to experience comparable strain boundary conditions to those existing in the field. In the marketing and development of the centrifuge, these benefits must be stressed.

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